SPACEBORNE GPS FOR EARTH SCIENCE

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INTRODUCTION

With the recent completion of the Global Positioning System constellation and the appearance of increasingly affordable spaceborne receivers, GPS is moving rapidly into the world of space flight projects. Indeed, owing to the great utility and convenience of autonomous onboard positioning, timing, and attitude determination, basic navigation receivers are coming to be seen as almost indispensable to future low earth missions. This development has been expected and awaited since the earliest days of GPS. Perhaps more surprising has been the emergence of direct spaceborne GPS science and the blossoming of new science applications for high performance geodetic space receivers.

Applications of spaceborne GPS to Earth science include centimeter-level precise orbit determination (POD) to support ocean altimetry; Earth gravity model improvement and other enhancements to GPS global geodesy; high resolution 2D and 3D ionospheric imaging; and atmospheric limb sounding (radio occultation) to recover precise profiles of atmospheric density, pressure, temperature, and water vapor distribution. Figure 1 offers a simplified summary of the Earth science now emerging from spaceborne GPS.

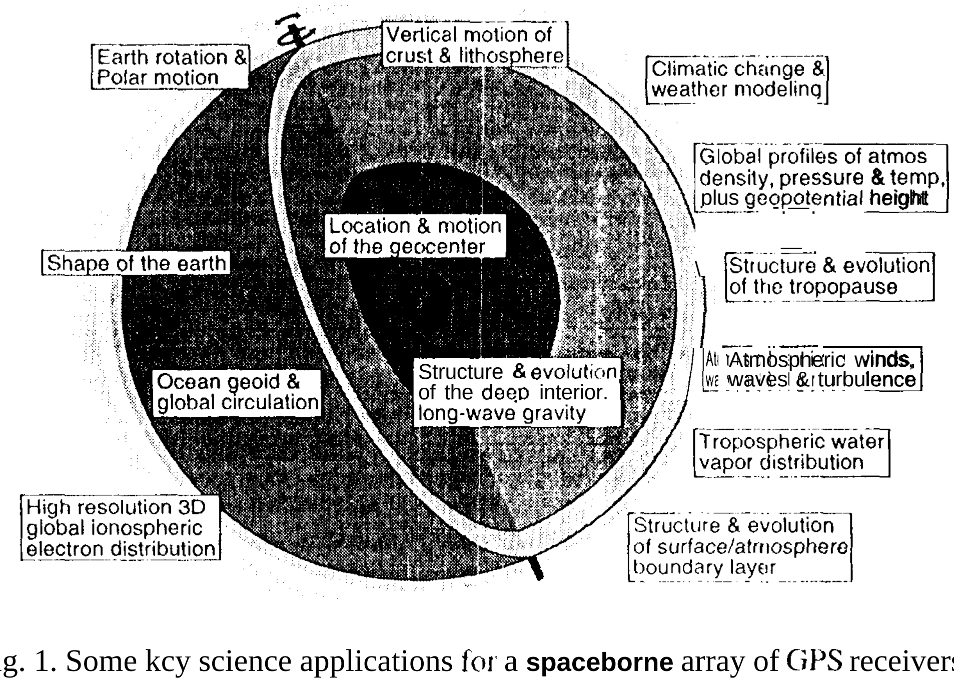


Fig. 1. Some key science applications for a **spaceborne** array of GPS receivers,

Consistent with these different uses, there has developed in recent years a two-tiered user community for GPS in space: those. seeking basic, modcralc-performance GPS navigation, timing, and (in some cases) attitude determination, and those pursuing the more demanding science activities requiring the highest performance dual-frequency receivers. As the mission-dependent requirements within each group are diverse, a variety of receiver models for space use has emerged. While that healthy situation is likely to continue, from the standpoint of the. scientists it may be hoped that in the future the high end instruments will reach levels of size, cost, and generality of function that will allow them to serve both user classes economically, thus converting the most utilitarian satellites into potentially powerful science instruments.

Conventional single- and dual-frequency GPS receivers have been flown in space for basic navigation and (increasingly) attitude determination on a number of recent missions. These include RADCAL, Christa-SPAS, Orbcomm, and MicroLab I, which carried the Trimble TANS Vector receiver for positioning and attitude determination [Cohen *et al*, 1993; *Lightsey et al*, *1994];* and several Space Shuttle. flights, which carried a dual frequency Rockwell-Collins 3M receiver, A variant of the Rockwell receiver, the AST V, was flown on two U.S. military satellites, the Air Force's TAOS (Technology for Autonomous Operational Survivability) and the Advanced Research Projects Agency's experimental DARPASAT [*Cubbedge and Higby*, 1994]. In addition, a 12-channel single-frequency P-code receiver built by Motorola was flown aboard NASA's Extreme Ultraviolet Explorer [Gold *et al*, 1994], and a 5-channel Japanese C/A-code receiver was flown on Japan's OREX mission [*Tomita et al*, *1994].*

As GLONASS becomes established as a reliable navigation system "we can expect to see considerably more commercial resources devoted to developing the technology for both the ground and space. A high performance spaceborne GPS/GLONASS receiver for navigation and science applications is currently under development by the European Space Agency and may fly within two years [*Silvestrin et al*, 1995].

The utilitarian spaceborne GPS applications represent, in essence, a fulfillment of the GPS vision. They exploit GPS, sometimes in clever ways, for purposes for which it was expressly intended. For the growing class of high-precision spaceborne science users surveyed here, the same cannot be said. GPS was not conceived with such uses in mind (indeed, their feasibility was generally recognized only after GPS deployment was well underway), and has not been altered in any way to accommodate them. Within these diverse scientific enterprises we find many examples in which GPS innovators have, through ingenuity and industry, coaxed a reluctant system to perform unexpected feats, thereby expanding the GPS mission. In the face of the seriously confounding security features known as selective availability and anti-spoofing, they have extracted from GPS levels of performance undreamed of by its architects. The following sections summarize recent highlights in spaceborne GPS science and sketch a picture. of its promising future.

PRECISE ORBIT DETERMINATION AND GRAVITY IMPROVEMENT

The first of these unconventional GPS applications to be seriously examined was precise orbit determination (POD) in support of high precision ocean altimetry. A global differential GPS technique for achieving sub-decimeter orbit accuracy on the joint U. S.-French Topex/Poseidon mission was first proposed at the Jet Propulsion Laboratory in 1981. The basic elements of the proposed differential GPS

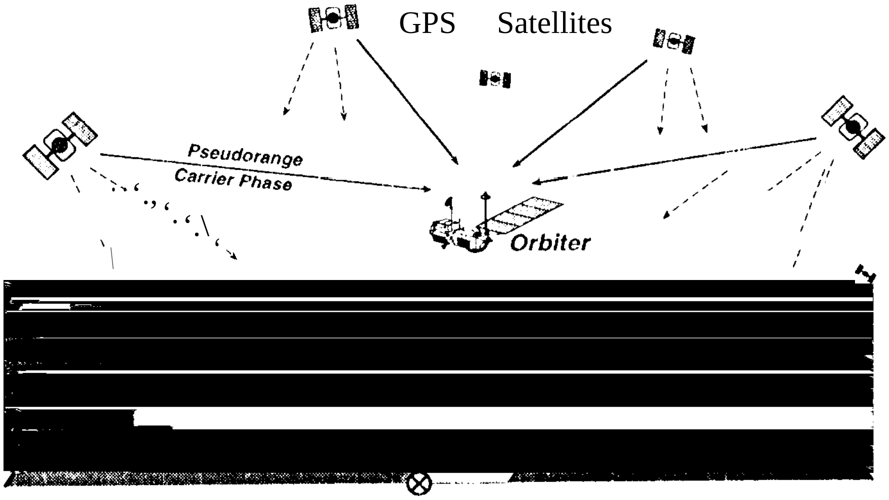


Fig. 2. Key system elements for precise orbit determination with differential GPS.

The Topex/Poseidon ocean altimetry satellite was launched into a 1300 km orbit on an Ariane rocket in August of 1992. It carried an experimental dual-frequency P-code receiver built by Motorola to test these new tracking techniques [*Melbourne et al*, 1994]. The Topex GPS POD demonstration has now surpassed pre-launch expectations of 5-10 cm radial orbit accuracy by about a factor of three.

A number of aspects of this experiment are notable: (1) conventional dynamic differential GPS orbit solutions were essential y equivalent to dynamic solutions obtained with laser and DORIS (Doppler) tracking data, with radial accuracies of 3-4 cm RMS [*Schutz et al*, 1994]; (2) reduced dynamic orbit solutions, in which the unique geometric strength of GPS data is used to minimize sensitivity to force model errors [*Wu et al*, 1991] consistently improved upon dynamic solutions (judged primarily by altimeter crossover agreements) to yield radial orbit accuracies of 2-3 cm RMS [*Yunck et al*, 1994; *Bertiger et al*, 1994; *Hesper et al, 1994];* (3) University of Texas investigators used GPS data from Topex/Poseidon to improve the Earth gravity model over what had earlier been achieved by tuning with laser and DORIS data, leading to significantly reduced geographically correlated dynamic orbit error [*Bertiger et al*, 1994]; *(4)* dynamic orbits with a GPS-tuned gravity model surpass those with a laser/Doppler-tuned model, but fall short (by -1 cm RMS) of GPS reduced dynamic orbits [*Bertiger et al, 1995]; (5)* GPS-based orbits of the highest accuracy are now obtained with a fully automated, unattended processing system; (6) analysis based on Topex results suggests that reduced dynamic orbit accuracies of a few centimeters should be achievable for future missions at altitudes below 500 km [*Melbourne et al*, 1994; *Bertiger et al*, 1995]; (7) recent unpublished results by Ron Muellerschoen at JPL indicate that carefully tuned onboard dynamic filtering could yield real time non-differential orbit accuracies of a few meters under nominal levels of selective availability.

Since the Topex/Poseidon receiver cannot decrypt the Y-codes, the. GPS demonstration has been partially in abeyance since anti-spoofing , ame on nearly full time in January of 1994. Routine processing continues, however, with L1 C/A-code data, yielding radial accuracies in the range of 4-5 cm RMS, itself a somewhat surprising result. In the wake Of the Topex success, GPS-based POD has been adopted for several future altimetry missions, including the U.S. Navy's Geosat Follow On, which will carry a Rockwell MAGR and is slated for a 1996 launch, and the Topex/Poseidon Follow-On, proposed for launch later in the decade.

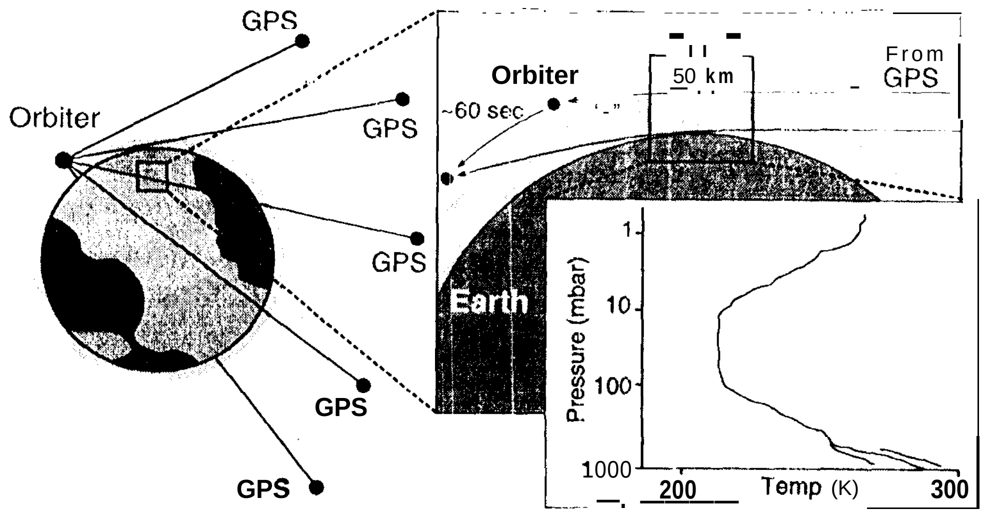


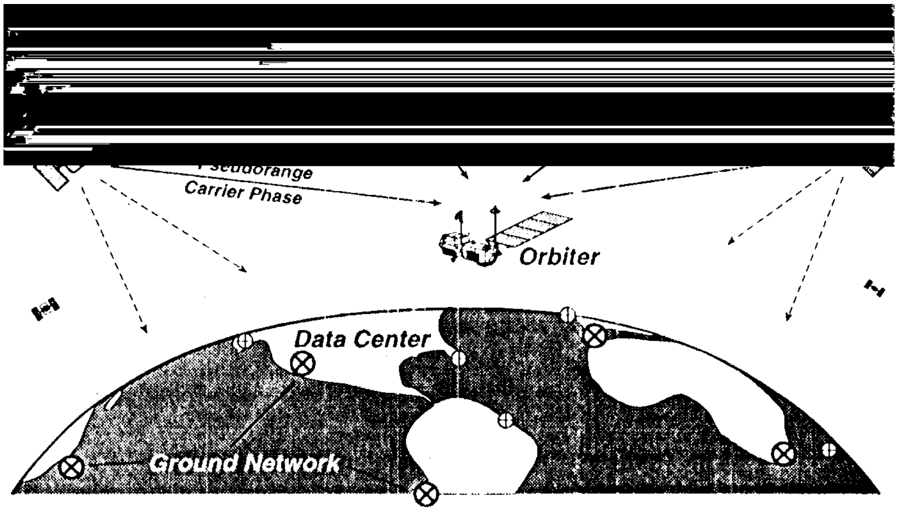
Fig. 3. Illustration of atmospheric temperature profiling by GPS occultation

GPS ATMOSPHERIC OCCULTATION

The probing of planetary atmospheres by radio occultation dates to the early 1960s when Mariners 3 and 4, viewed from Earth, passed behind Mars [*Kliore et al*, 1964 and 1965]. In this technique a radio signal from a spacecraft moving behind a planet is tracked until blockage. As the signal cuts through the planet's refractive atmosphere., its lengthening path delay, revealed by the observed change in phase delay or Doppler shift, can yield a precise profile of the atmospheric density, pressure, temperature or water vapor, and, to some degree, composition and winds. Amplitude variations can expose atmospheric turbulence and wave structure.

While radio occultation has probed many planets and moons throughout the solar system, it has as yet found no useful application to Earth, for two reasons. First, the observation requires both a radio source and a suitable receiver off the planet, outside the atmosphere; seldom have we had such matched pairs in Earth orbit. Second, to be of use in studying Earth's atmosphere, whose nature we know well, such measurements must be continuous, comprehensive, synoptic. We therefore need many transmitters and receivers aloft at once, densely sampling the global atmosphere every few hours. Until the arrival of GPS and low cost microsats, the evident cost of such an enterprise made it impractical within Earth science programs.

In the late 1980s, a group at JPL proposed observing GPS signals from space to make atmospheric soundings by radio occultation, as shown in Fig. 3 [*Yunck and Melbourne, 1989]*. Briefly, the observed Doppler shift in the GPS signal induced by atmospheric bending permits accurate estimation of the atmospheric refractive index. From that one can retrieve, in sequence, profiles of the atmospheric density, pressure, and temperature (or, in the lower troposphere, water vapor) with high accuracy (<1 Kelvin in temperature) and a vertical resolution of a few hundred meters [



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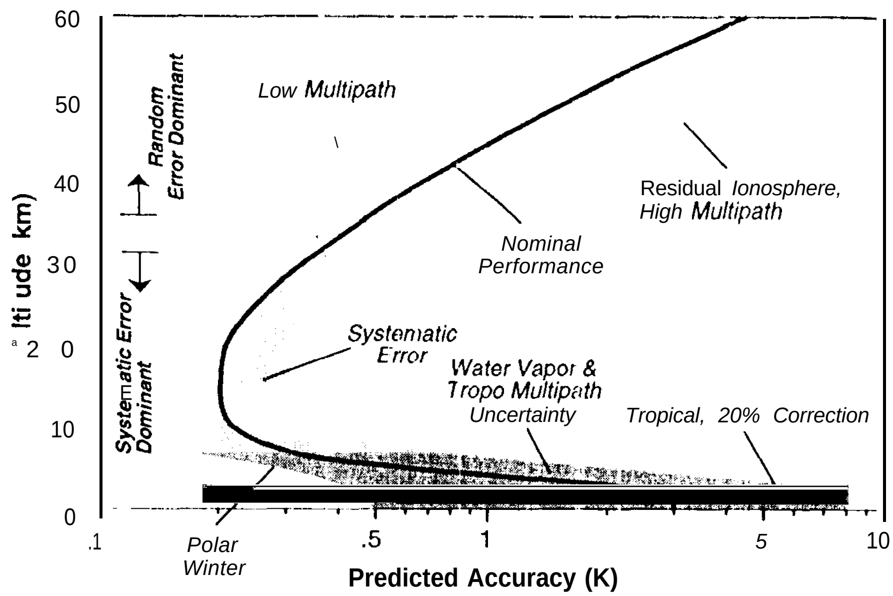

Fig. 4. Estimated GPS-derived atmospheric temperature accuracy vs altitude.

A single satellite can recover more than S00 profiles each day, distributed almost uniformly around the globe; a large constellation would recovei many thousands of profiles, which could one day have a profound impact on both long term climatological studies and short term weather modeling. In addition, such an array would enable high resolution 3D tomographic imaging of the ionosphere (see next section) and would serve many geodetic uses (e.g., gravity recovery, geocenter monitoring) as well.

Stimulated by the original JPL proposal, a group led by the University Corporation for Atmospheric Research in Boulder, CO, succeeded in obtaining sponsorship from the U.S. National Science Foundation for a low-cost demonstrate ion experiment called GPS/MET (for meteorology), to fly as an acid-on payload to a NASA experiment (an Optical Transient Detector) aboard Orbital Sciences Corporation's MicroLab 1 satellite. Additional mission support was provided by NOAA (the National oceanic and Atmospheric Admin - istration) and the FAA (Federal Aviation Administration), and supplemental analysis support was obtained from NASA, To acquire the occultation data, Allen Osborne Associates, manufacturer of the Turbo Rogue geodetic GPS receiver, developed a ruggedized flight version known as the TurboStar, J]'']., a collaborator on the experiment, revamped the receiver soft ware for autonomous operation and occultation scheduling in space. The TurboStar produces 50 Hz dual frequency data samples during occultations using the

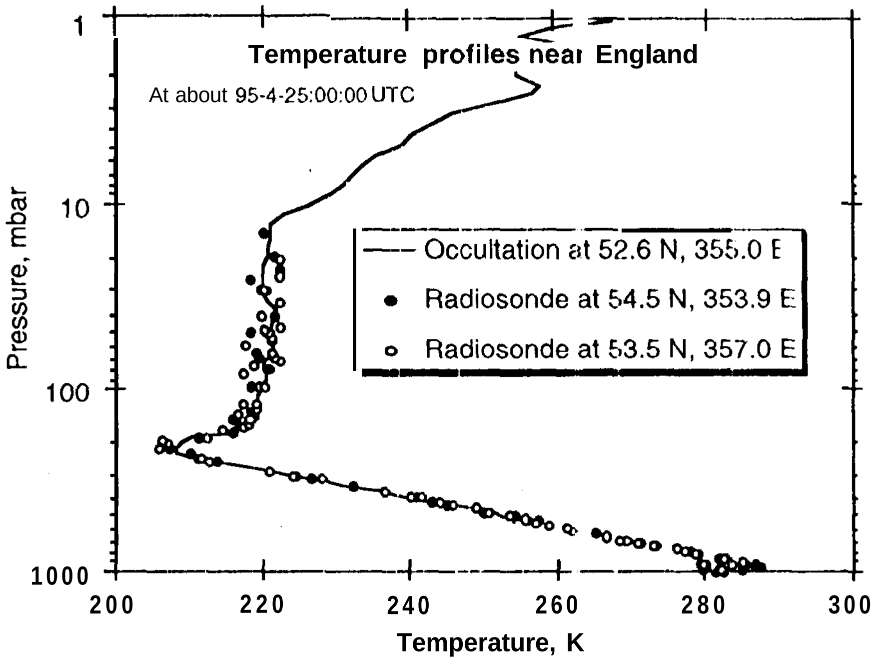

Fig. 5. Typical GPS atmospheric temperature. profile compared with two radiosondes.

The best occultation data are acquired with P-code tracking during occasional periods when anti spoofing is off, and JPL has been able to negotiate several such periods, each lasting typically a few weeks, with the Department of Defense. Initial profiles recovered by groups at JPL, UCAR, and the University of Arizona are extremely encouraging, in many cases with estimated accuracies of about 1 Kelvin over a wide range of altitudes [e.g., *Hajj et al*, *1995]*. This performance is expected to improve steadily as analysis refinements are introduced, Ionospheric studies with the GPS/MET data are just now beginning and as yet no results have been reported.

IONOSPHERIC IMAGING WITH SPACEBORNE GPS

The dual frequency GPS signals offer a direct means of pleasuring the integrated or total electron content (TEC) along the line of sight from the receiver to the GPS satellites [e.g., *Yunck*, 1993]. Today, ionospheric measurements from the global GPS ground network are used to generate accurate global maps of zenith TEC [*Mannucci et al,* 1993]. Such maps are valuable both for calibration of tracking data from other satellites and for scientific study of the ionosphere. While ground-based zenith TEC maps represent a big advance in our ability to image the ionosphere, they have their limitations. Horizontal resolution is still relatively crude, though that will improve with more ground sites, and information on the vertical electron distribution is entirely absent. Various efforts have been made to recover vertical information from ground based TEC data by means of two-dimensional tomography, but the basic observing geometry severely limits the vertical resolution that can be achieved through the ionosphere to provide exquisite vertical resolution; combined data from large numbers of space- and ground-based receivers will enable high resolution two- and three-dimensional snapshot imaging of the global ionosphere [*Hajj et al*, *1994]*.

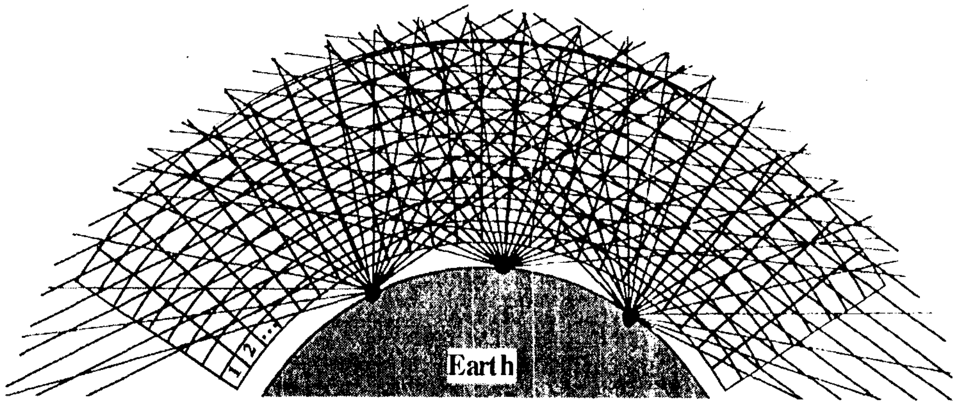

Fig. 6, Ionospheric sampling with combined ground and spaceborne GPS receivers.

Figure 6 illustrates in two dimensions the ionospheric sampling that can be achieved from the ground and space. Simulation studies performed by *Hajj et* time variation; and (2) pairs of low-orbiting microsats flying in formation on which modified GPS receivers would make both conventional "high-low" GPS measurements to observe the long-wavelength gravity components, and more precise "low-low" satellite-satellite range and Doppler measurements (with accuracies of -10 p m and -1 μm/s) to observe the shorter wavelength components, up to about degree and order 80. No such mission has yet been approved.

Several planned international microsat missions will carry versions of the TurboStar for atmospheric occultation and gravity modeling. These include the Danish Ørsted and the South African Sunsat missions, set to be launched together on a Delta rocket in 1997, and a possible Brazilian SACI mission in 1998. In addition, a TurboStar is expected make occultation observations from the Wakeshield facility, to be deployed and retrieved by the Space. Shuttle this year; another will be placed aboard the Russian MIR space station in 1997 for a timing experiment in cooperation with the Smithsonian Astrophysical Observatory. At least a half-dozen other TurboStar flights are in the discussion stage.

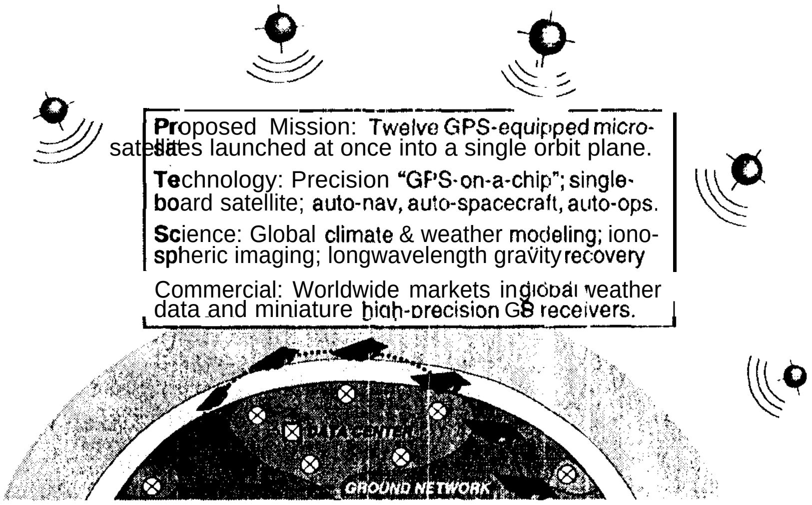

Fig. 7. Concept for a pilot constellation of spaceborne GPS receivers for Earth science.

While the individual occultation missions will serve to advance the GPS technology and validate its capabilities, they will do little for atmospheric science. It is the fervent hope of the growing GPS occultation community that a small pilot constellation of a dozen or so microsats will be sponsored either by government agencies or by commercial interests (eyeing a potential worldwide market in GPS weather products) in the very near future. One such concept being developed at JPL is shown in Fig. 7. This could be the prelude to an array of hundreds of tiny, autonomous satellites continuously monitoring the global atmosphere and ionosphere three-dimensionally, with high resolution in space and time (while also improving the gravity model), within a decade. The results from GPS/MET have made the prospect of such a mission tantalizing, and the prospects for its eventual deployment highly promising.

DISCUSSION

GPS is quickly achieving a routine presence in space for the basic utility functions of real time onboard state determination, precise time and frequency transfer, and moderate precision attitude determination, and is likely to be the method of choice for those tasks for many future Earth satellites, both American anti international. At present, real time onboard position accuracies fall in the 50-100 m range, limited by the instantaneous effects of SA dither, which typically introduces 20-30 m errors in measured pseudorange. Experiments on EUVE and Topex/Poseidon (and an earlier simulation study by *Bar - Sever et al [1990])* show that robust onboard dynamic filtering can smooth real time position error to a few meters, with SA dither at its nominal level. Similarly, onboard time determination, typically accurate to a few tenths of a microsecond today, can be improved to a few tens of nanoseconds through filtering,

The best current GPS-derived attitude accuracies are reported to be. a few tenths of a degree, or about 20 arcmin, with antenna baselines of 1 m, A recent study by *Young* [1995] suggests that continued improvements in passive and active multipath suppression combined with real time dynamic filtering can reduce attitude error by more than an order of magnitude, to about 1 arcmin, with performance ultimately limited by the accuracy of the antenna phase center calibration,

Demonstrations of combined GPS/GLONASS in space are still more than a year away. In 1994 the European Space Agency began development of a high performance dual frequency GPS/GLONASS receiver for spaceborne science applications, The receiver will have a minimum of 12 parallel channels, each able to track either GPS or GLONASS signals at high rates, and will be able to track by means of the P-codes, C/A-codes, and several codeless techniques, The first prototypes could be available. by the end of 1995 [*Silvestrin et al*, *1995]*. While the future of GPS for spaceborne usc appears to be secure, it remains to bc seen whether GPS/GLONASS will gain a solid foothold in the market.

Spaceborne GPS for Earth science is in the exciting early phase of invention, with promising developments underway in geodesy, climatology, weather modeling, and ionospheric imaging. The advancement of spaceborne GPS science is rapidly becoming an international venture, with small missions in preparation in a number of countries. These science applications invariably require high performance dual-frequency receivers with capabilities well beyond the utility needs of most civilian missions. in the near term there will therefore remain two distinct classes of GPS usc in space. It may one day come to pass, however, that as science programs move towards the creation of a large constellation of GPS microsats, the size and cost of high end flight receivers will approach that of utility models, and many more satellites will then be able to contribute to spaceborne GPS science.

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